Variations and Attribution Analysis of Mountain-Outlet Runoff of Major Rivers in the Shule River Basin from 1956 to 2021: Postprint

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Abstract

Based on measured runoff data from mountain-outlet hydrological stations of the Shule River, Shiyou River, and Dang River from 1956 to 2021, together with meteorological data from the Tuole Meteorological Station and reanalysis datasets, this study employs Sen' s slope estimator and the Mann-Kendall test to analyze the characteristics and causes of runoff variation in the three rivers. The results indicate: (1) From 1956 to 2021, the outflow runoff of all three rivers exhibited increasing trends, with the Shule River and Dang River showing statistically significant increases, while the Shiyou River showed a non-significant increasing trend. (2) The abrupt change years for the three rivers occurred in 1998, 2007, and 1982, respectively, with runoff increasing significantly after the change points; the change rate for the Shule River was 60%, while those for the Shiyou River and Dang River were approximately 20%. (3) The runoff of the Shule River and Shiyou River entered a high-flow period after the 2000s during the study period, whereas the Dang River increased slowly after the 1980s and reached historically high flow values in the early 2020s. (4) Under the combined influence of increased fluctuating precipitation and accelerated glacier melting caused by rising temperatures after 1986, both the annual average and seasonal flows of the outflow runoff in the three rivers showed increasing trends.

Full Text

Changes in Runoff from Major Rivers and Analysis of Its Causes in the Shule River Basin from 1956-2021

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Abstract

Based on measured runoff data from the mountain outlet hydrological stations of the Shule River, Shiyou River, and Dang River from 1956-2021, combined with meteorological data from the Tuole station and reanalysis data, this study analyzed the characteristics and causes of runoff changes in the three rivers using the Mann-Kendall test and Sen' s slope estimator. The results indicate: (1) Runoff from all three rivers showed an increasing trend, with the Shule River and Dang River exhibiting significant increases, while the Shiyou River showed a non-significant increase. (2) The abrupt change years for the three rivers were 1998, 2007, and 1982, respectively. After the abrupt change, runoff increased significantly, with the Shule River increasing by 60%, and the Shiyou River and Dang River increasing by approximately 20%. (3) The Shule River and Shiyou River experienced abundant water periods after the 2000s, while the Dang River increased slowly after the 1980s and showed historically high values in the early 2020s. (4) Under the combined influence of increased fluctuating precipitation and accelerated glacier melting caused by rapidly rising temperatures after the 1980s, both the annual average and seasonal flow of the three rivers showed increasing trends.

Keywords: Shule River Basin; mountain outlet runoff; variation; causal analysis

Introduction

According to the IPCC Sixth Assessment Report, global warming has become the dominant trend of climate change. Climate change-induced temperature increases, regional precipitation variations, and accelerated snow/ice melt and permafrost degradation have altered regional water cycle processes. The Shule River, located in the western Hexi Corridor, features numerous high mountain systems. Water vapor transport among these lofty mountains results in relatively low precipitation, but well-developed glaciers and snow cover at high altitudes, with runoff primarily formed by precipitation and snow/ice melt. Water resources required for regional socioeconomic development have exhibited new variation characteristics. For the ecologically fragile arid and semi-arid inland river basins in northwest China, changes in meteorological elements such as temperature and precipitation have attracted widespread attention, consequently leading to new trends and characteristics in river runoff and basin water resources. As one of the three major inland river basins in the Hexi Corridor, the Shule River Basin, situated deep in the interior of northwest China, has experienced significant changes in mountain outlet runoff under climate change impacts, drawing considerable scholarly attention. The variation patterns of meteorological elements and runoff within the basin are crucial for regional socioeconomic development and scientific utilization and management of water resources.

Previous analyses of runoff variation characteristics in the Shule River Basin under climate change have primarily focused on the eastern Shule River mainstream. Studies have analyzed and simulated runoff variation characteristics from 1960-2010, showing that annual runoff at Changmabao, Dangchengwan, Shuangtabao, and Panjiazhuang stations along the Shule River mainstream all exhibited increasing trends, with the mountain outlet Changmabao station increasing by 13.87% per decade and the abrupt change year occurring in 1997. Zhang et al. analyzed data from 1956-2015 and found that temperature, precipitation, and runoff in the Shule River all showed upward trends, with the abrupt point occurring in 1997. Sun et al. analyzed data from 1956-2015 at the Changmabao station and indicated an increasing trend in runoff. Zhang Wenchun found that runoff at the Changmabao mountain outlet station from 1950-2015 showed an increasing trend, with the abrupt point in 1997 and an average multi-year flow increase of 56.1%. Li et al. used a distributed hydrological model for cold regions to quantitatively simulate runoff components and their variation characteristics in the upper Shule River, showing that glacier runoff, snowmelt runoff, rainfall runoff, and baseflow accounted for 30.5%, 12.9%, 13.5%, and 43.1% of total runoff, respectively. Due to increasing temperature and precipitation trends, both glacier runoff and rainfall runoff showed increasing trends with average increases of 4.66$\times10^{6}$ $m^3 \cdot a^{-1}$ and 1.01$\times10^{6}$ $m^3 \cdot a^{-1}$, respectively, while snowmelt runoff showed a decreasing trend with an average reduction of 2.46$\times10^{6}$ $m^3 \cdot a^{-1}$. Lan et al. found that from 1960-2010, temperatures in the upper mountainous areas of the three major inland river systems in Hexi (Shiyang River, Heihe River, and Shule River) generally showed an upward trend.

Li et al. simulated future scenarios and found that precipitation also showed an increasing trend, but with intense interannual fluctuations, and the main contribution to annual runoff increase was snow/ice melt. Li et al. studied runoff from various rivers in the Shule River Basin from 1960-2010 and found a continuous increasing trend, with groundwater recharge accounting for 40.46% of runoff. The mountain outlet runoff of the Shule River mainstream was abundant from 2001-2010. Li used a distributed hydrological model to analyze temperature, precipitation, and runoff elements in the Shule River Basin from 1979-2018, simulating variation trends of mountain flow under different scenarios, indicating that Shule River mountain outlet runoff generally showed an increasing trend. Yang et al. showed that precipitation influence increased significantly after the 1990s, with temperature influence on runoff exceeding approximately 50%. The above research results provide technical support for comprehensive water resource planning and scientific management of the Shule River Basin.

However, research on the Shule River Basin has mostly concentrated on the Shule River mainstream or individual rivers, focusing primarily on evolution trends, abrupt change years, and wet/dry periods of temperature, precipitation, and runoff. Systematic analysis of variation characteristics and causes of mountain outlet runoff for the entire Shule River Basin and its major rivers over the past decades is still lacking. Therefore, this study selects the entire Shule River Basin as the research area to explore variation characteristics and differences of temperature, precipitation, and runoff elements of the three major rivers (Shule River, Shiyou River, and Dang River) from 1956-2021, aiming to provide a scientific basis for comprehensive management and utilization of water resources in the Shule River Basin.

1.1 Study Area Overview

The Shule River Basin is located at the western end of the Hexi Corridor, between 92°11 -98°30 E and 38°00 -42°48 N. The main rivers from east to west are the Shule River, Shiyou River, and Dang River (Fig. [Figure 1: see original paper]). The Shule River originates from the Gangger Xiaohéli Ridge of the Qilian Mountains with a source elevation of 4737 m. Its mainstream flows from southeast to northwest between the Tuolai Nanshan and Shule Nanshan, with a total length of 583 km and a catchment area of 4.13$×10^{4}$ km^2. The length from source to the Changmaxia mountain outlet (Changmabao Hydrological Station) is 347 km. The Shiyou River originates from the central Zhaobi Mountain with a source elevation of 4737 m, consisting mainly of high mountains, canyons, low mountainous areas, and gobi desert basins. The Dang River, at the westernmost end of the Shule River Basin, originates from the glacier groups of Bengkun Daban and Zailimuke in the Shule Nanshan, and Bayin Zeerkengwule and Nuogannuoer in the Danghe Nanshan. Its mainstream flows from southeast to northwest with a total length of 379 km. The study area generally exhibits a plateau mountain climate characteristic.

1.2 Data Sources

The study selected Changmabao Station on the Shule River, Yumen City Station on the Shiyou River, and Dangchengwan Station on the Dang River as research objects. Meteorological data were obtained from the China Regional Ground Meteorological Elements Forcing Dataset (CMFD) (National Tibetan Plateau Data Center) reanalysis data [cite]. Considering the lack of national meteorological stations in the Shule River Basin, meteorological data from Yuerhong within the basin and nearby Tuole were selected for reference analysis. Hydrological and meteorological station information is shown in Table . Runoff data are measured annual values from the three river hydrological stations from 1956-2021. Runoff data and Yuerhong meteorological station data were obtained from the "Hydrological Yearbook of the People' s Republic of China" ; Tuole meteorological station data were obtained from the China Meteorological Data Service Center (http://data.cma.cn).

1.3 Research Methods

Sen' s Slope Estimator

Sen' s slope estimator was used to analyze annual runoff variation trends at each hydrological station in the study area. The formula is: β = median(xj - xk)/(j - k) for all j > k, where xj and xk are time series data values at times j and k, respectively. The sign of β (greater than or less than 0) reflects whether the trend is upward or downward, and its magnitude indicates the slope steepness.

Mann-Kendall Test

The Mann-Kendall test was used to conduct trend and abrupt change tests on runoff, temperature, and precipitation changes at the three river hydrological stations and meteorological stations in the study area. The Mann-Kendall test is a non-parametric test recommended by the World Meteorological Organization and widely used for trend analysis of hydrological and meteorological time series. Its detailed formulation can be found in references [cite]. Its advantages include not requiring normal distribution of samples and being insensitive to individual outlier values.

[Figure 1: see original paper] Location of hydrological stations and meteorological stations in the study area

Basic information of hydrological stations and meteorological stations in the study area

2 Results and Analysis

2.1 Interannual Variation Characteristics

2.1.1 Interannual and Seasonal Variation As shown in Fig. [Figure 2: see original paper], both the Shule River and Dang River passed the 0.01 significance level trend test, while the Shiyou River did not pass the 0.05 significance level test. Trend test results showed that runoff from all three rivers exhibited an increasing trend. Except for spring runoff in the Shiyou River, which showed a decreasing trend, seasonal variations for all other seasons were increasing. Overall, the Shule River and Dang River showed significant increasing trends, while the Shiyou River showed a non-significant increasing trend.

Table shows that from a linear trend perspective, the average runoff of the Shule River, Shiyou River, and Dang River all showed increasing trends. The Sen' s slope estimated change rates for the Shule River and Dang River were larger, at $0.36\times10^{8}\ m^3\cdot(10a)^{-1}$ and $0.34\times10^{8}\ m^3\cdot(10a)^{-1}$, respectively, while the Shiyou River was $0.02\times10^{8}\ m^3\cdot(10a)^{-1}$.

From the 5-year moving average, the Shule River showed an increasing trend after the 1980s; the Shiyou River was stable from the 1950s-1970s, decreased from the 1980s-1990s, increased from the 1990s-2010s, and then decreased again after the 2010s; the Dang River was stable from the 1950s-1970s, slightly decreased from the 1970s-1980s, and then increased again after the 1980s.

Fig. [Figure 2: see original paper] and Table show the multi-year variation characteristics and C values of measured runoff at the three hydrological stations in the Shule River Basin from 1956-2021. The C values at Changmabao Station on the Shule River and Yumen City Station on the Shiyou River were 0.36 and 0.34, respectively, with large interannual variation amplitude and extreme value ratios of 4.13 and 3.83. The C value at Dangchengwan Station on the Dang River was 0.29, with smaller interannual variation amplitude and an extreme value ratio of 3.47. The maximum annual runoff for all three rivers occurred in the 2010s, while the minimum annual runoff for the Shule River and Dang River occurred in the 1960s, and for the Shiyou River in the 1970s.

2.1.2 Interdecadal Variation As shown in Fig. [Figure 3: see original paper], interdecadal variations differ slightly among the three rivers in the Shule River Basin. The Shule River was in a dry period before the 1990s, reached its maximum wet period value in the 2000s, and slowed down in the early 2010s. The Shiyou River was in a dry period in the 1960s-1970s, reached a wet period in the 2000s, and showed a dry period in the 2010s-2020s. The Dang River was in a dry period in the 1960s-1980s, showed an increasing trend in the 1990s-2000s but with reduced increase, reached a wet period maximum in the 2010s, and showed a slight decline in the early 2020s. Overall, the runoff evolution trends of the Shule River and Dang River were roughly dry-wet-dry-wet, while the Shiyou River was wet-dry-wet-dry. All three rivers showed peak wet period values in the 2010s during the study period.

2.1.3 Abrupt Change Characteristics of Runoff As shown in Table , Mann-Kendall test results indicated that the abrupt change years for Changmabao Station on the Shule River, Yumen City Station on the Shiyou River, and Dangchengwan Station on the Dang River were 1998, 2007, and 1982, respectively. Compared with pre-abrupt change periods, post-abrupt change annual runoff showed significant increases, with the Shule River showing the largest change rate at 60%, and the Shiyou River and Dang River at approximately 20%.

2.2 Intra-annual Runoff Variation Characteristics

As shown in Table and Fig. [Figure 4: see original paper], intra-annual runoff distribution among the three rivers in the Shule River Basin is extremely uneven. The Shule River and Shiyou River have the largest uneven distribution, showing single-peak patterns (July-August), while the Dang River is relatively smaller, showing a double-peak pattern (May and August). Runoff from the Shule River and Shiyou River is mainly concentrated in the flood season from June-September, with maximum monthly runoff in August. The Dang River' s intra-annual runoff distribution is more uniform compared to the Shule and Shiyou Rivers, with spring and summer accounting for 62.9% of runoff.

After the abrupt change, the intra-annual runoff hydrographs of all three rivers became steeper, specifically manifested by increased peak values and slower autumn recession processes. Winter runoff at Changmabao Station on the Shule River and Dangchengwan Station on the Dang River increased, while no significant change occurred in the Shiyou River. In terms of monthly runoff change rates, the Shule River and Shiyou River showed the largest winter runoff change rates, while the Dang River was relatively 平缓 and smaller throughout the year.

3 Discussion

For the three major rivers in the Shule River Basin, the amount of water from upstream mountainous areas is mainly affected by precipitation and temperature changes, with minimal impact from human activities in high-altitude mountainous regions.

3.1 Response of Runoff Variation to Precipitation Change

Precipitation is the main driving factor for runoff changes at the mountain outlets of the three rivers in the Shule River Basin. The Shule River Basin belongs to the western Qilian Mountains, where the terrain and altitude differences are relatively large, and climate characteristics in different altitude zones are distinct. From the perspective of water vapor sources and occurrence frequency, precipitation is mainly influenced by the westerlies. However, there are very few meteorological stations with observation data in the Shule River Basin, only the Yuerhong rainfall station. Therefore, the China Regional Ground Meteorological Elements Forcing Dataset (CMFD) from the National Tibetan Plateau Data Center was used to plot precipitation variation trends above the mountain outlets of the Shule River, Shiyou River, and Dang River (Fig. [Figure 5: see original paper]), with reference to Yuerhong and Tuole meteorological station data for comparative analysis.

The results show that annual precipitation above the mountain outlets of the three rivers generally shows a weak increasing trend, with multi-year average precipitation of 272.9 mm, 216.5 mm, and 329.1 mm for the Shule River, Shiyou River, and Dang River, respectively, and change rates of 10.4 mm $\cdot$ $(10a)^{-1}$, 11.3 mm $\cdot$ $(10a)^{-1}$, and 11.3 mm $\cdot$ $(10a)^{-1}$. Fig. [Figure 6: see original paper] shows that compared with the Shiyou River and Dang River, the Shule River has a better precipitation-runoff correlation, reaching 0.65. Precipitation-runoff correlations for the Shiyou River and Dang River are weaker, at 0.45 and 0.48, respectively.

Regarding precipitation in the Qilian Mountains, Lan et al. found that northwestern Qilian Mountains precipitation generally shows an increasing trend, with dry years before the 1990s and wet years after the 1990s. Xu et al. studied precipitation in the upper Shule River from 1960-2014 and found an increasing trend, with an abrupt change from less to more precipitation around 1986. Zhang et al. showed that temperature, precipitation, and runoff in the Shule River all showed significant positive abrupt changes in 1997, presenting obvious increasing trends. Comparing the precipitation variation trend with the three rivers' runoff variation trend (Fig. [Figure 5: see original paper]), the Shule River and Shiyou River showed stable periods in runoff variation trends from the 1970s-1990s, while the Dang River showed a slight decline period from the 1970s-1980s, which correlates well with precipitation variation trends.

3.2 Response of Runoff Variation to Temperature Change

Temperature is also an important factor affecting runoff from the three rivers in the Shule River Basin. Over the past 60 years, temperature increases or decreases have significantly impacted processes such as ice/snow melt and runoff generation and concentration in permafrost-covered areas. Due to the lack of measured temperature data in the Shule River Basin, temperature data from the nearby Tuole meteorological station were used to analyze temperature variation trends.

From 1956-2021, the annual average temperature at Tuole Station showed a weak upward trend with a rate of 0.36 ℃ • $(10a)^{-1}$. Previous studies also indicated that the annual average temperature in the Shule River source area and mountain outlet increased significantly at rates of 0.40 ℃ • $(10a)^{-1}$ and 0.34 ℃ • $(10a)^{-1}$, respectively. Research shows that low-temperature extremes in northwest China' s arid regions abruptly changed around 1986, after which temperature showed significant enhancement. The temperature trend at Tuole Station (Fig. [Figure 7: see original paper]) shows that temperature remained basically stable from 1956-1986 with a multi-year average of -3.07 ℃, while from 1987-2021, temperature showed a continuous increasing trend with a multi-year average of -1.81 ℃. The annual temperature change rates of the Shule River, Shiyou River, and Dang River vary slightly due to different regional locations, but the general trend is consistent.

Under the background of temperature increase, changes in underlying surfaces dominated by cryospheric elements such as glaciers have significantly impacted interannual and intra-annual runoff distribution and runoff generation mechanisms in cold region basins in western China. Glaciers and permafrost develop in the high-altitude mountainous areas above the outlets of the Shule River, Shiyou River, and Dang River. According to glacier inventory data, the Shule River has the largest glacier coverage area and ice storage in the Qilian Mountains at 509.87 km^2 and 203.77 km^2, respectively. Research also shows that under climate warming, Shule River glacier meltwater has shown an increasing trend since the 1990s, and a turning point in glacier meltwater may occur within 10-20 years.

In summary, precipitation and temperature are the main driving factors for runoff changes at the mountain outlets of the three rivers in the Shule River Basin. Precipitation in the entire study area shows a fluctuating increasing trend, while temperature accelerated after 1986, causing accelerated glacier melting. Under the combined influence of precipitation and temperature, both annual average and seasonal flow of the three rivers show increasing trends. Permafrost degradation is the main reason for increased winter flow in the Shule River.

4 Conclusions

From 1956-2021, mountain outlet runoff from major rivers in the Shule River Basin showed an overall increasing trend, with the Shule River and Dang River showing significant increases and the Shiyou River showing a non-significant increase.

The abrupt change years differed among the three rivers: 1998 for the Shule River, 2007 for the Shiyou River, and 1982 for the Dang River. After the abrupt change, interannual runoff increased significantly, with the Shule River showing the largest change rate at 60%, and the Shiyou River and Dang River at approximately 20%.

Interdecadal wet/dry variations differed among the three rivers. The Shule River was dry from the 1950s-1990s, reached maximum wet period values in the 2000s, and was wet in the 2010s. The Shiyou River was dry in the 1960s-1970s, reached a wet period in the 2000s, and was dry in the 2010s-2020s. The Dang River was dry in the 1960s-1980s, wet in the 1990s-2000s, reached wet period maximum values in the 2010s, and showed a slight decline in the early 2020s.

Intra-annual distribution showed that except for non-significant spring decrease in the Shiyou River, all others showed increasing trends. After the abrupt change, intra-annual monthly distribution hydrographs became steeper, with the Shule River showing the most significant change.

Precipitation and temperature are the main driving factors for mountain outlet runoff changes in the three rivers. Precipitation in the entire study area shows a fluctuating increasing trend, while temperature accelerated after 1986, causing accelerated glacier melting. Under the combined influence of precipitation and temperature, both annual average and seasonal flow of the three rivers show increasing trends. Permafrost degradation is the main reason for increased winter flow in the Shule River.

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Note: Figure translations are in progress. See original paper for figures.